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SUSTAINABLE DEVELOPMENT

Environmental and economic optimisation of the floor on grade in residential buildings

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Abstract
Purpose The goal of the study was to determine the preferred composition of the floor on grade in residential buildings in the Belgian context from a life cycle environmental and financial perspective. In addition to the life cycle costs, the required investments were evaluated to take into account budget restrictions. The analysis of current available materials and techniques allows both the designer and building owner to extend their decision criteria from mainly investment cost to life cycle aspects as well.
Methods In this study, the potential environmental impact was assessed by considering the environmental external cost of the floors. Several existing methods were combined to enable a full assessment, taking the ExternE methodology (willingness to pay) as the main base. The ecoinvent database was used to gather the inventory data but was adapted to increase the representativeness for Belgium. The financial evaluation included both the investment and life cycle aspects. The latter was analysed through the sum of the present values of all costs occurring during the life span of the floor.
Results and discussion The necessary assumptions (e.g. transport, end-of-life treatment, cleaning, life span, economic parameters) and the adaptations to the ecoinvent data are transparently reported. The methodological steps (e.g. monetary valuation, transmission losses, equivalent degree days, Pareto optimisation) are elaborated in detail. This allows the results, which are graphically presented, to be correctly interpreted. The contribution of the life cycle stages and the optimisation potential of the considered impacts are discussed.
Conclusions The environmental external cost based on the willingness to pay to reduce environmental impacts proved to be relatively low, representing about 9 % of the financial cost. The cost reduction of current common practice was estimated to be about 20 and 60 % from a financial and environmental perspective, respectively. The insulation level and the floor covering were identified as the most important optimisation parameters.
Recommendations Internalisation of environmental external costs might be an important step to achieve more sustainable solutions. However, it is recommended to consider financial and environmental external costs separately too because both contain important information for the decision maker. Because it is hard (if not impossible) to increase the insulation level of the floor on grade later on in the life cycle of the building, a high insulation value should be a priority during construction. The floor covering can more easily be adapted and is thus considered a secondary priority.

Keywords Budget restrictions · Floor on grade · Life cycle assessment · Life cycle costing · Monetary valuation · Pareto optima

1 Introduction

Architects and building owners are confronted with questions as: How much insulation should be foreseen in the floor on grade, in the roof and outer walls? Which type of glazing should be chosen? Which floor covering is preferred? When designing buildings, the investment cost is most often an important decision criterion and the only cost estimated in terms of affordability. To date, this is certainly common for small-

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scale residential buildings within the private housing sector in Belgium. To move towards more sustainable buildings, both the life cycle environmental impact and the costs should be considered as well. The importance of considering both from the early design stage is amongst others confirmed by Castella et al. (2009). In the presented study, both aspects were investigated to search for the optimal solutions for 16 residential buildings within the Belgian context. The evaluation focused on currently available materials and techniques and searched for the preferred solutions both from an environmental and financial point of view. The optimisation of the buildings focused on the choice of materials and services and insulation level and not on the geometric characteristics. The latter were, however, addressed by comparing the 16 different case studies. The research comprises comparative analyses of non-identical functional units to determine which performance should be strived for. All consequences of the choices made (e.g. heating energy for non-identical insulation level, cleaning activities for non-identical finishes and replacements for non-identical life spans of building components) were, however, taken into account. In order to allow a detailed assessment of many alternatives, the analysis was performed in several steps. During the first step, the different building elements (e.g. outer walls, foundation, inner walls, floors and roofs) were investigated separately but assessed as integrated in the building related to their life cycle according to ISO 15392 (2008). From these detailed analyses, the most preferred solutions were retrieved for analysis at the building level (of the 16 residential buildings). This paper elaborates on the assessment of one of these elements, more specifically the floor on grade.

The approach chosen consists of expressing both the financial and environmental impacts in monetary values. Environmental impacts are to date not paid by the end-user and are therefore often referred to as external (environmental) costs. Internalising these costs makes the 'polluter' pay for the environmental consequences of his behaviour, and it is therefore assumed that internalising these costs will influence his behaviour and decisions. Although this approach does include a high degree of uncertainty compared to midpoint approaches, it seems most appropriate for its higher decision support capacity (Bare et al. 2000) and communication strength. The latter is important to reach the building owners. Although this article includes a description of the methodology to enable a correct interpretation of the results presented, the focus is not a methodological discussion. This is elaborated in previous publications (Allacker 2010; Allacker and De Nocker 2012).

2 Goal and scope

The first phase in a life cycle assessment study consists of the goal and scope definition (ISO 14040:2006). This section is limited to the aspects which are common for both the environmental and economic assessment. The aspects which relate only to the environmental assessment, i.e. data requirements, assumptions, limitations, impact categories, assessment method and interpretation approach, are described in Sections 3 and 6.

2.1 Goal

The goal was to search for the most preferred solutions for the floor on grade in newly built residential buildings from both an environmental and financial point of view. The aim was to consider the whole life cycle and assess all currently available materials and techniques on the Belgian market. The results should allow both the designer and the building owner to gain a better insight into the life cycle impact and cost of their choices and to make more informed decisions. The goal was moreover to integrate the environmental and cost aspects to enable straightforward decision making in contradictory cases. To determine the best choice within the available budget, the research aimed for a method which included budget restrictions. Beside this goal to provide valuable information during the first design phase for architects, building owners and other stakeholders, a second goal was to investigate the optimisation potential of common practice to date.

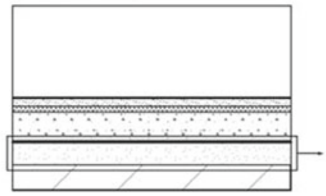
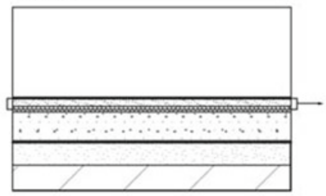
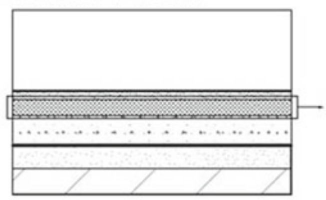
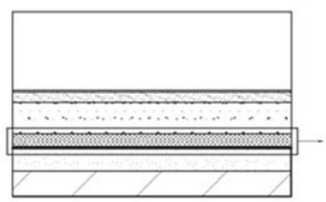
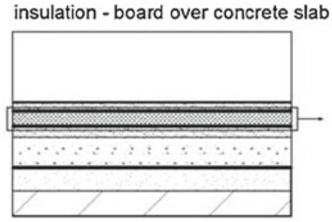
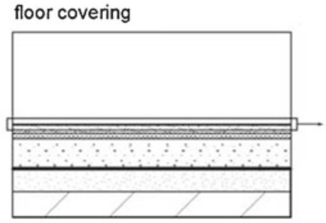
2.2 Scope

Out of all currently available building materials and techniques, the analysis had to be limited to those for which the required environmental data were available. This selection resulted in 79 alternatives, differentiating in floor bed filling, screed, insulation type and thickness, and floor covering (Fig. 1).

The alternatives were defined in such a way as to focus on the different layers of the floor. All consequences that the choice for a certain layer had upon the other layers were taken into account. The screed thickness for example varied with the insulation thickness according to the building requirements in Belgium (BBRI 1994). Finally, a reference floor was defined which represents common practice to date. It consists of a floor bed filling of 10 cm compacted sand, a PE sheet, a reinforced concrete slab (15 cm), 3 cm polyurethane (PUR) foam, a cement-based screed (5 cm) and ceramic tiles (1 cm) (upper drawing in Fig. 1 with the first floor bed filling).

2.3 System boundaries

Within the life cycle of the floor on grade, different stages can be distinguished. The analysis included the production of the required materials (cradle to gate), transport of the materials to the construction site, construction (limited to

floor composition for the optimisation of the layer indicated	options analysed for the specific layer
floor bed filling  ceramic tiles - 1 cm screed cement based - 5 cm PUR foam - 3 cm concrete slab (reinforced) - 15 cm PE sheet floor bed filling	- compacted sand: 10 cm - gravel: 10 cm - expanded clay aggregates: 10 cm - concrete: 5 cm
screed  ceramic tiles - 1 cm screed PUR foam - 3 cm concrete slab (reinforced) - 15 cm PE sheet compacted sand - 10 cm	- cement based: 5 cm - anhydrite binder - 5 cm - insulating screed, EPS aggregates - 5 cm - insulating screed, EPS aggregates - 10 cm
insulation - PUR foam  ceramic tiles - 1 cm screed cement based - 5 cm PUR foam concrete slab (reinforced) - 15 cm PE sheet compacted sand - 10 cm	PUR foam: 3 - 4 - 5 - 6 - 8 - 10 - 12 - 15 - 18 - 21 cm
insulation - board under concrete slab  ceramic tiles - 1 cm screed cement based - 7 cm concrete slab (reinforced) - 15 cm insulation board PE sheet compacted sand - 10 cm	- PUR: 4 – 8 – 10 – 12 – 18 - 24 cm - resol: 4 – 8 – 10 – 12 – 18 – 24 cm - EPS: 4 – 8 – 10 – 12 – 18 – 24 cm - XPS: 4 – 8 – 10 – 12 – 18 -24 cm
insulation - board over concrete slab  ceramic tiles - 1 cm screed cement based, reinforced - 7* cm PE sheet insulation board PE sheet leveling course cement based - 7 cm concrete slab (reinforced) - 15 cm PE sheet compacted sand - 10 cm	- PUR: 3 - 5 - 8 - 10 - 15 - 20 cm - rock wool: 3 - 5 - 8 - 10 - 12 - 18 - 24 cm - resol: 4 - 8 - 10 - 12 - 18 - 24 cm - EPS: 4 - 8 - 10 - 12 - 18 - 24 cm - XPS: 4 - 8 - 10 - 18 - 20 cm
floor covering  floor covering screed cement based - 5 cm PUR foam - 3 cm concrete slab (reinforced) - 15 cm PE sheet compacted sand - 10 cm	- ceramic tiles - tiles of blue stone (BE) - tiles of blue stone (Asia) - parquet – hardwood (BE mix) (**) - laminate - cork - linoleum - carpet - PUR-floor

(*) The screed thickness varies with the insulation thickness according to the TV193 of BBRI (BBRI 1994, p. 43).

(**) For the parquet covering, an extra PE sheet is foreseen above the PUR foam and, consequently, the cement based screed is reinforced.

Fig. 1 Composition of the analysed variants of the floor on grade

material losses during construction), use stage (cleaning, maintenance, replacements, heating demand due to transmission losses), demolition (limited to energy demand), transport to the end-of-life (EOL) treatment and the EOL treatment. The latter includes landfill, incineration, re-use and recycling (including sorting processes).

2.4 Functional unit

The functional unit defines a reference for normalisation (ISO 14040:2006). Because the aim was to compare different options for the floor on grade in a fixed building, 1 m^2 of floor in a heated room (18°C) of a residential building was chosen as functional unit. The function of the room can be any room (e.g. living room, bedroom, entrance hall, kitchen) with a ‘normal’ use and thus ‘normal’ cleaning and maintenance requirements (e.g. not a garage). It is, however, up to the designer or building owner to choose the appropriate floor covering for the function of the room (e.g. no carpet in the kitchen). Because interested stakeholders (e.g. architects, engineers, quantity surveyors) are accustomed to work with this unit, the results are easily accessible by them.

A building life span of 60 years was assumed, which equals the average age of dwellings in Belgium (Ammar and Longuet 1980; FOD economie, K.M.O., Middenstand en Energie 2009). Necessary replacements of the floor covering within this life span of 60 years were included in the analysis. More specifically the following replacements were considered (BCIS 2006; Inies 2009):

- Parquet, hardwood: at 30 years
- Laminate, cork, linoleum, carpet, PUR-covering: every 15 years

3 Environmental impact assessment

3.1 Life cycle inventory

For each of the life cycle stages, the data collection, sources and a summary of the data are provided in the subsequent paragraphs.

The *production stage* covers the cradle-to-gate data of the occurring materials. The inventory data were retrieved from the ecoinvent version 2.0 database (ecoinvent 2009), which were harmonised to improve their representativeness for the Belgian context. The adaptation was made by the Flemish Institute for Technological Research (VITO) and concerned the replacement of the Swiss electricity mix (electricity, medium voltage, at grid/CH) by the European alternative (electricity, medium voltage, production RER, at grid/RER). It was thus assumed that building materials on the Belgian market were produced in Europe. The adaptations were, however, limited to the first level, meaning that only the electricity that is needed directly to produce the respective materials (virgin ecoinvent records) was changed.

An analysis was made of the occurring materials for each of the floor variants. The amount of materials was determined, and the best available representative ecoinvent record for each material was selected. This is illustrated for the reference floor in Table 1. A similar approach was used for the other floor variants.

Because the majority of the wood products in Belgium are imported (from outside Europe), it was necessary to consider the specific Belgian situation concerning the mixed use of local and imported wood. The Belgian mix hardwood scenario, summarised in Table 2, was mainly based on a report of the Belgian timber importers federation (Belgian Federation of Timber import 2007). However, several other sources were also consulted to complete the lacking data, amongst others (Frère 2008; MINEFI-DGTPE 2007; Swedish Forest Industries Federation 2007; Institut forestier national (Ifn) 2008). This detailed literature study was done by the Belgian Building Research Institute (BBRI).

Because data were lacking concerning the *transport of the materials to the construction site*, a survey was conducted by the BBRI in 2008. For several material categories, the average distances and transport means were surveyed. Based on this questionnaire, the assumed transport scenarios of the materials applied in the different floor variants are summarised in Table 3.

The *construction stage* was limited to the material losses occurring during the construction process. An average loss of 5 % was assumed without differentiating between the materials. In future analysis, a differentiation between different material categories might be necessary; however, data were lacking during this research.

The *use stage* consists of cleaning, maintenance and replacements on the one hand and of heating due to transmission losses on the other hand. An overview of the cleaning and maintenance scenarios is provided in Table 4. These scenarios were based on several literature sources (ASPEN 2008b; UPA-BUA 2009; Hollander den et al. 1993; Pasman et al. 1993). Double counting was excluded by eliminating the maintenance processes type 1 (higher frequency) when these occurred at the same time as maintenance process type 2 (lower frequency). The number of replacements of the floor covering is defined by dividing the life span of the floor (60 years) by the life span of the floor covering (see Section 2.4) minus 1.

The energy demand due to heating during the use stage can only be estimated at the building level. In order to take into account the contribution of the floor on grade on the heating demand, the heat loss due to transmission was considered. This allowed a full assessment and an investigation into the relative importance of energy compared to materials. The heat resistance of the floor was calculated according to the Flemish Energy Performance Building Directive (EPBD). More specifically, the

Table 1 Composition of the reference floor, mentioning the selected ecoinvent records

Layer	Material	Amount/m² floor	Ecoinvent record (adapted)
Compacted sand (10 cm)	Sand	180 kg (1,800 kg/m³×0.1 m)	Sand, at mine/CH
PE sheet	Polyethylene	0.2 kg	Polyethylene, HDPE, granulate, at plant/RER extrusion, plastic film/RER
Reinforced concrete slab (15 cm)	Concrete	0.149 m³ [(1×1×0.15) - (volume reinforcement)]	Concrete, normal, at plant/CH
	Reinforcement	10.522 kg [(π×(0.008/2)²×1×7,850)kg/bar×((100/15)×2×2)bars]	Reinforcing steel, at plant/RER
PUR foam (3 cm)	Polyurethane foam	1.05 kg (35 kg/m³×0.03 m)	Polyurethane, flexible foam, at plant/RER
Cement-based screed (5 cm)	Portland cement	11.5 kg	Portland cement, strength class Z 52.5, at plant/CH
	Sand	60 kg	Sand, at mine/CH
	Water	6 kg	Tap water, at user/RER
Ceramic tiles	Ceramic tiles (44.6×44.6×1 cm)	25.102 kg (5.083 kg/tile×4.938 tiles)	Ceramic tiles, at regional storage/CH
	Cement mortar joints (0.4 cm)	0.336 kg (0.068 kg/tile×4.938 tiles)	Cement mortar, at plant/CH
	Glue	2.5 kg	Phenolic resin, at plant/RER
	Water	0.7 kg	Tap water, at user/RER

Table 2 Transport scenario of 1 m³ hardwood according to the current Belgian situation

Hardwood—Belgian mix	1 m³
Local wood	0.596 m³
Imported tempered wood	0.217 m³
Imported tropical wood	0.187 m³
Lorry, >16 tons	290 ton km
Transoceanic tanker	1,689 ton km
Freight, rail	32 ton km
Barge	35 ton km

simplified method (Dutch norm) of the EPBD (formula 1) was followed (a.a. 2007, pp. 57226–57227). This method was selected because it is independent of the dwelling type, the length/width ratio of the floor and its size.

$$U_0 = U_{\text{floor}} \times \alpha = U_{\text{floor}} \times \frac{1}{1 + U_{\text{floor}}} \quad (1)$$

with U_0 the U value of the floor and U_{floor} the U value of the floor from indoors to the floor surface in contact with the ground, both expressed in watts per square metre kelvin.

The heating demand was estimated based on the equivalent degree days (eq. °days) (DPWB 1984). The number of eq. °days per year was determined through the analysis of a detached and terraced house, assuming an average indoor air temperature of 18°C in accordance to the EPBD. For both dwellings, the number of eq. °days was calculated for different insulation values (K value[1]). The glazed area and the air tightness of the dwellings were varied because these are important parameters. It is noticed that the number of eq. °days linearly evolves with the K value of the dwellings. The lower the K value, the lower the number of eq. °days. Based on the analysis, 1,200 eq. °days were selected as basic scenario because this corresponds with well-insulated dwellings (Fig. 2). This therefore enables to determine the optimal insulation thickness of the floor on grade assuming that the other elements are also well insulated; 1,700 eq. °days were chosen as a sensitivity analysis to investigate the importance of heating and to determine the most optimal insulation value of the floor in less insulated dwellings. For both cases, a standard/high-performance heating system (global installation efficiency=68 %) on natural gas was assumed (DPWB 1984). Although not elaborated in this article, the results of the dwelling analysis (calculating the heating demand according to EPBD instead of the eq. °days) coincided with the ones retrieved from the element analyses (Allacker 2010) and thus confirm the choice of 1,200 eq. °days as a good estimate.

The impact due to *demolition* was incorporated by assuming a fixed impact per kilogram of demolished or

[1] The K value of a building refers to its total insulation value (a.a. 2007).

Table 3 Transport scenarios of the building materials to the construction site (per ton)

Material	Lorry >16 t, fleet average/RER (ton km/ton)	Lorry 3.5–16 t, fleet average/RER (ton km/ton)	Van <3.5 t/RER (ton km/ton)	Barge/RER (ton km/ton)
Floor bed filling	43.5	10.8	1.7	0.1
PE sheet	74.7	23.4	2.0	
Concrete (in situ)	43.5	10.8	1.7	0.1
Reinforcement	74.7	23.4	2.0	
Insulation materials	74.7	23.4	2.0	
Screed	43.5	10.8	1.7	0.1
Screed reinforcement	74.7	23.4	2.0	
Covering				
Carpet, linoleum, tiles, laminate	73.0	20.8	1.2	
Cement mortar for tiles	43.5	10.8	1.7	0.1
Parquet, cork	74.7	23.4	2.0	
Varnish (cork)/wood wax (parquet)	50.9	19.8	38.5	
PUR-floor	74.7	23.4	2.0	
PUR-floor: quartz sand	43.5	10.8	1.7	0.1

dismantled material. No distinction was made between the different materials. For the demolition or dismantling process, the ecoinvent record for the disposal of concrete (not reinforced) was adapted by VITO to a general demolition record. More specifically from the ecoinvent record 'Disposal, building, concrete, not reinforced, to final disposal/CH', the transport process (*transport, lorry 20–28 t, fleet average/CH*) and the disposal process (*disposal, inert waste, 5 % water, to inert material landfill*) were eliminated.

For the *transport to the EOL treatment*, a survey was conducted by the BBRI in 2008. For several material categories, the average distances and transport means were surveyed. Based on this questionnaire, the assumed transport scenarios of the materials to the EOL treatment are summarised in Table 5.

Again a survey was conducted by the BBRI in 2008 for the *EOL treatment of the materials*. For several material categories, the EOL treatment was surveyed. The resulting scenarios (% mechanical sorting, % landfill, % incineration, % re-use and % recycling) are summarised in Table 5. For the several EOL treatment processes of the different materials, the appropriate ecoinvent record was selected. This is illustrated for the reference floor in Table 6. If for recycling and re-use 'avoided production' is mentioned in the table, this means the original product (as mentioned in Table 1) is assumed to be avoided.

The mechanical sorting process is assumed identical for all materials and modelled based on the ecoinvent record 'disposal, building, bulk iron (excluding reinforcement), to sorting plant—CH'. This record was modified by assuming the following for 1 kg of material to be sorted:

- Input:
  - Handling in sorting plant—0.000141 m^3 of 'Excavation, hydraulic digger/RER'

Table 4 Cleaning and maintenance scenarios for the different floor coverings

Covering	Cleaning		Maintenance type 1		Maintenance type 2	
	Process	Frequency	Process	Frequency (years)	Process	Frequency (years)
Tiles	Vacuum–clean mop	Weekly			Joints (1 tile/m^2 floor)	15
Parquet	Vacuum–clean	Weekly	Beeswax	1	Scrub+beeswax	15
Laminate	Vacuum–clean mop (water)	Weekly			Repair (10 %)	10
Cork	Vacuum–clean	Weekly	Polish	1	Scour, scrub and varnish	5
Linoleum	Vacuum–clean mop	Weekly				
Carpet	Vacuum–clean	Weekly	Shampoo clean, repair of seams (5 %)	2	Repair (10 %)	10
PUR-floor	Vacuum–clean mop	Weekly				

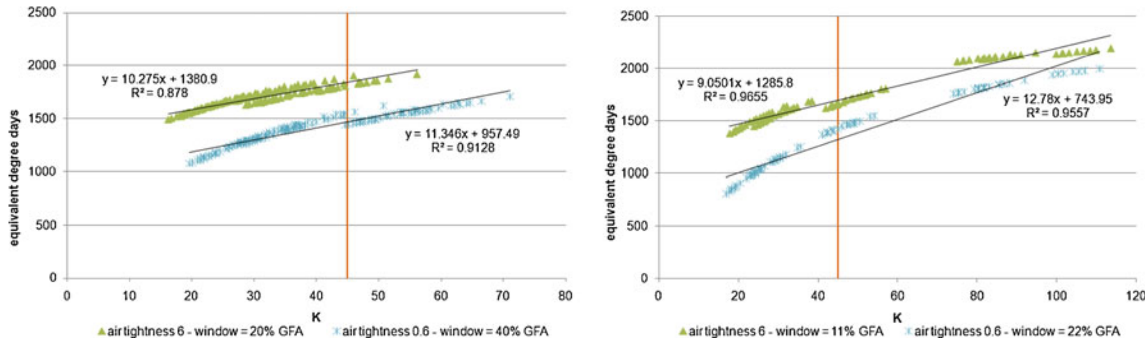


Fig. 2 Calculation of the equivalent degree days for a detached and terraced dwelling (*GFA* gross floor area; Allacker 2010, p. 107)

– Energy: demand in sorting plant: 0.0022 kWh of 'Electricity, low voltage, production RER, at grid/RER'
– Sorting plant infrastructure—1.0e^{-10} of 'Sorting plant for construction waste/CH'

• Output:

– Emission in sorting plant—0.00792 MJ, heat, waste

3.2 Life cycle impact assessment—monetary valuation

The aim was to include as many impacts as possible despite the uncertainty of some of these. Moreover, the aim was not only to consider the inventory data and impacts but also to calculate a single score to enable straightforward decisions in case of contradictory indicators. It is important to note that, when disclosed to the public, a comparison of the alternatives based on the single score is not in line with ISO 14044 (2006).

In order to allow an integrated assessment of impacts and costs, the impacts were expressed in monetary values, referred to as external costs (European Commission 2008; Mizsey et al. 2009; Swarr 2006). These are costs the society and/or future generations must carry because of the social or economic activities of a single person or a group of people. The latter thus do not fully account for their impacts. Within this research, the external costs were mainly based on the willingness to pay approach and were retrieved by combining different existing methods. The considered emissions and impacts together with the external costs are summarised in Table 7 (Holland et al. 2005; Davidson et al. 2002; European Commission 2008; Torfs et al. 2005; Ott et al. 2006; EC 2006; De Nocker et al. 2007). A detailed discussion on external costs, monetary values and an extended justification of the selected methods was elaborated in Allacker (2010) and Allacker and De Nocker (2012).

Table 5 Transport to the EOL treatment (per ton) and EOL treatment scenarios of the building materials

Material	Lorry >16 t, fleet average RER (ton km/ton)	Lorry 3.5–16 t, fleet average RER (ton km/ton)	Van <3.5 t RER (ton km/ton)	Barge RER (ton km/ton)	Landfill (%)	Incineration (%)	Re-use (%)	Recycling (%)	Mechanic sorting (%)
Floor bed filling									
Sand	53.2	10.1	3.4		0	0	58	42	83
Other	33.5	17.8	1.7		5	0	30	65	65
PE sheet	37.6	13.5	5.5	0.0073	0	0	4	96	79
Concrete (in situ)	33.5	17.8	1.7		5	0	30	65	65
Reinforcement	37.4	7.8	4.2		0	0	2	98	12
Insulation materials	45.4	11.6	6.1		100	0	0	0	88
Screed	33.5	17.8	1.7		5	0	30	65	65
Screed reinforcement	37.4	7.8	4.2		0	0	2	98	12
Covering									
Carpet	37.6	13.5	5.5	0.0073	0	0	4	96	79
Linoleum	45.6	20.7	4.4		27	73	0	0	60
Tiles (+ joints)	33.5	17.8	1.7		5	0	30	65	65
laminate	65.7	11.5	5.5		0	4	41	55	73
Parquet	93.0	11.5	5.4		0	13	17	70	70
Cork	30.8	26.1	6.1		88	0	12	0	88
PUR-floor	45.6	20.7	4.4		27	73	0	0	60

Table 6 Reference floor: selection of the most appropriate ecoinvent records for the EOL treatment

Layer	Landfill	Re-use	Recycling
Compacted sand	–	Avoided production, no impacts	
PE sheet	–	Avoided production	0.6 kWh of 'Electricity, medium voltage, production RER, at grid/RER[b]+avoided production
Concrete slab	'Disposal, building, concrete gravel, to final disposal/CH'	Avoided production of 'Gravel, crushed, at mine/CH'	'Disposal, building, cement-fibre slab, to recycling/CH'+ avoided production of 'Gravel, crushed, at mine/CH'
Reinforcement	–	Avoided production	'Recycling steel/iron'[c]+avoided production
PUR foam	'Disposal, building, polyurethane sealing, to sorting plant/CH'	–	–
Cement-based screed	'Disposal, building, cement (in concrete) and mortar, to final disposal/CH'	Avoided production of 'Gravel, crushed, at mine/CH'	'Disposal, building, cement-fibre slab, to recycling/CH'+ avoided production of 'Gravel, crushed, at mine/CH'
Screed reinforcement	–	Avoided production	'Recycling steel/iron'[c]+avoided production
Ceramic tiles	'Disposal, building, brick, to final disposal/CH'[a]	Avoided production of 'Gravel, crushed, at mine/CH'	'Disposal, building, brick, to recycling plant/CH'[a]+avoided production of 'Gravel, crushed, at mine/CH'

[a] Best available approximation

[b] Based on study of TNO-MEP report 'Ecoefficiency of recovery scenarios of plastic packaging' (2001)

[c] Data record in SimaPro from Pré Consultants from the Netherlands. This record links to ecoinvent processes but has not been reviewed by ecoinvent. The environmental impacts of this process are included in the input of the secondary raw material from technosphere

Although in economics the standard approach to deal with future costs is discounting (next section), in LCIA there is, as yet, no consensus. Sáez and Requena (2007) made an overview of different discount approaches in literature and mention that all of the reviewed literature—except one—consider it appropriate (even essential) to discount future effects with some positive discounting. Although there is no consensus on which discount rate to use, a broad preference is given to use social discount rates, which are lower than the private discount rate. In this study, a social discount rate was assumed which is 1 % lower than the private one.

Table 7 Summary of the considered emissions/impacts and the monetary values

Emission/impact	External cost	Unit	Source
Airborne emissions, impacts on human health and crops			
$PM_{2.5}$	61,000	€/ton	ExternE-CAFE (Holland et al. 2005, pp. 13–17, mid-estimate, data for Belgium)
SO_2	11,000	€/ton	
NO_x	5,200	€/ton	
NH_3	30,000	€/ton	
VOC	2,500	€/ton	
Greenhouse gasses (calculated according to CML2000)			
CO_2 equivalents	50	€/ton equivalent	Davidson et al. (2002)
Impacts calculated according to Eco-Indicator 99			
Human health (except due to above emissions)	60,000	€/DALY	European Commission (2008), Torfs et al. (2005)
Quality of ecosystems	0.49	€/PDF m^2 year	Ott et al. (2006)
Depletion of resources	0.0065	€/MJ	EC (2006)
Freshwater	1.22	€/m^3	De Nocker et al. (2007)

CML Centrum Milieukunde Leiden, *DALY* disability adjusted life years, *PDF* potentially disappeared fraction

Table 8 Cleaning and maintenance cost for the different floor coverings

Cleaning		Maintenance 1		Maintenance 2	
Process	Cost (€/m^2)	Process	Cost (€/m^2)	Process	Cost (€/m^2)
Vacuum–clean mop	0.09	Parquet: beeswax	5.09	Tiles: joints	4.58
	0.14	Cork: polish	0.29	Parquet: scrub+beeswax	23.38
		Carpet: shampoo clean	3.52	Laminate: repair	6.00
		Carpet: repair of seams	0.07	Cork: scour, scrub, varnish	12.92
				Carpet: repair	1.23

4 Economic assessment

The *cost data* were mainly retrieved from a construction cost database valid for the Belgian context (ASPEN 2008a). The ASPEN database considers the material, labour and indirect costs for constructing (parts of) a building and is used to predict the investment cost of a building.

For the calculation of the *life cycle cost*, the investment cost was added to the sum of the present values of all future costs (during use and EOL stage). Assumptions had to be made concerning the price evolutions (growth rates) and the discount rate. Because these economic parameters are characterised by a high degree of uncertainty, a sensitivity analysis was made. For the basic scenario, a yearly real discount rate of 2 % was assumed. The yearly real growth rate for construction costs was assumed at 0.5 % and for the energy prices at 2 %. These assumptions were based on an analysis of the evolution of prices during the previous 50 years (Dexia Bank 2007; De Troyer 2007; ABEX 2009) and on predictions of price evolution in the future (Federaal Planbureau 2007; D'haeseleer 2007).

The *cleaning and maintenance* costs (Table 8) were retrieved from several sources as mentioned before. Because the costs from different sources dated from different years, a nominal value for the year 2008 was calculated using the ABEX (2009) index. The costs expressed in former Dutch Guilders were changed to euro assuming 1 guilder equals 0.4538 euro (2008).

Energy prices (for *heating and domestic hot water production*) differ between households due to the different producers in the current free market. In the analysis, the average gas price for households in Belgium in 2008 (European Commission 2009) was assumed and equals 0.0139 euro/MJ (including VAT and taxes).

The cost of the *waste removal and treatment* was based on an inquiry conducted by BBRI in 2009 addressing Belgian waste processors. Seven waste fractions were distinguished, for each of which a financial cost was determined based on the average real market prices from the different contractors. This resulted in the waste removal and treatment cost for the floor materials as summarised in Table 9.

Table 9 EOL removal and treatment (financial) cost of the building materials

Material	Cost (euro/ton)
Floor bed filling	
Sand	25
Other	17
PE sheet	46
Concrete (in situ)	17
Reinforcement	4
Insulation materials	30
Screed	17
Screed reinforcement	4
Covering	
Carpet	46
Linoleum	60
Tiles (+ joints)	17
Laminate	33
Parquet	34
Cork	26
PUR-floor	30

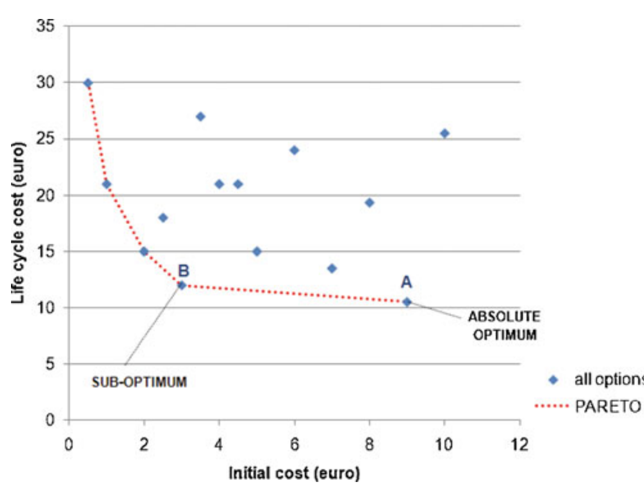


Fig. 3 Definition of 'absolute optimum' and 'sub-optimum' for a typical Pareto front

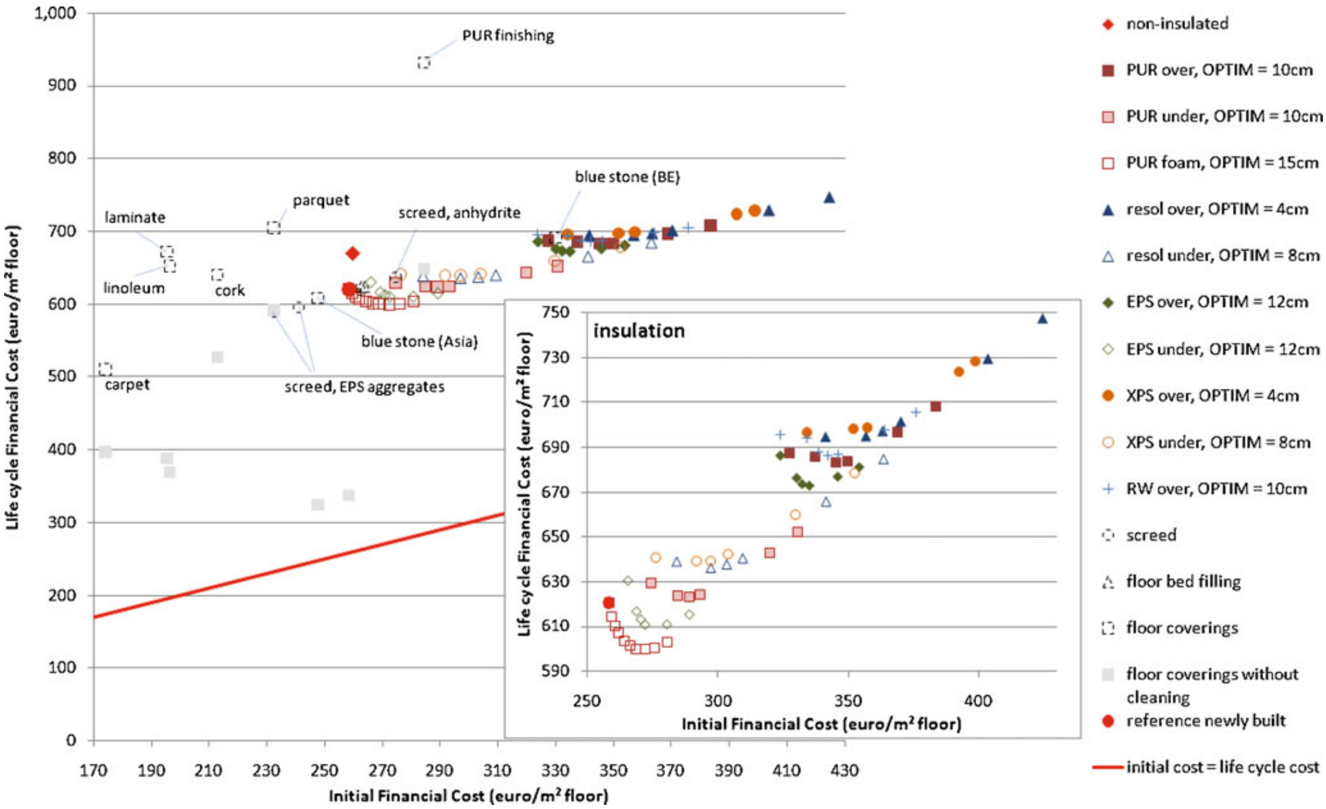


Fig. 4 Financial cost: overview of all analysed floor on grade alternatives

5 Internalisation of external costs

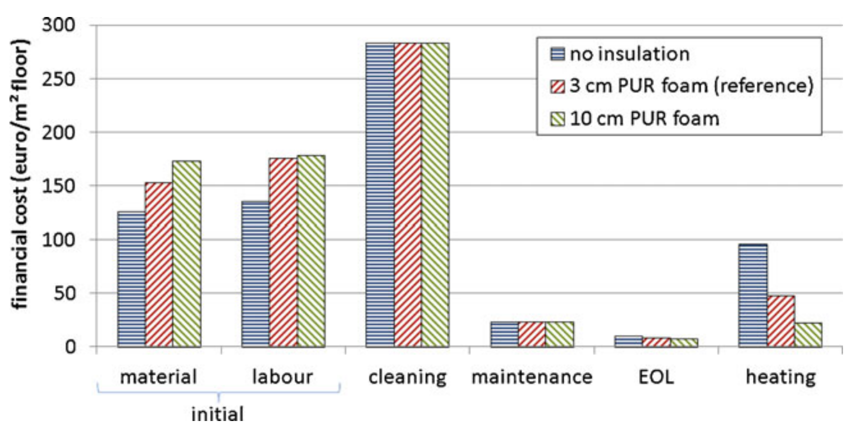
The sum of the financial (internal) and environmental external costs was calculated—defined as the total cost—in order to investigate whether internalisation of the environmental external costs would lead to different decisions. The integration of both aspects (see also Norris 2001) enables straightforward decisions to be made in case of contradictions. Such a political decision might moreover enhance the move towards more sustainable building solutions. To avoid confusion, for the remainder of the text, the term 'costs' is always preceded by 'financial', 'environmental (or external)' or 'total'.

6 Optimisation

The optimisation was based on the search for the Pareto optima out of a large number of options. According to the Pareto principle, the options from the considered population are optimal if there is no other option that improves one objective without simultaneously worsening at least one other objective (Marler and Arora 2004). The optimisation criteria were minimal initial and life cycle financial, environmental and total cost.

The Pareto fronts typically consisted of a steep decline for the options with a low initial cost and of a more

Fig. 5 Floor without insulation, 3 cm PUR foam (reference) and 10 cm PUR foam: the distribution of the life cycle financial cost over the life stages and processes



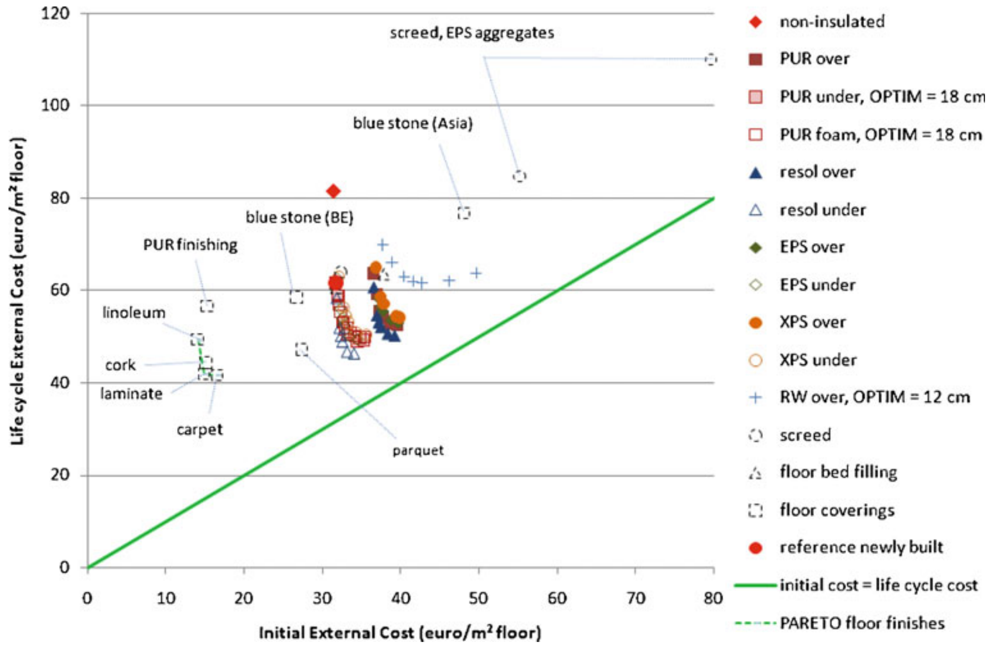


Fig. 6 External cost: overview of all analysed floor on grade alternatives

horizontal course for the higher investments (Fig. 3). The option with the lowest life cycle cost (option 'A') was defined as the 'absolute optimum' (of the considered population). However, this option requires a high extra investment for a relatively small reduction of the life cycle cost compared to option 'B' and can therefore be questioned. Presumably there are other more interesting investments (not necessarily related to the dwelling) to make. Option 'B' can therefore be seen as the most interesting and was defined as the 'sub-optimum'. Both the absolute and sub-optimum are valid if there is no budget restriction. The preferred option (lowest life cycle cost) within a certain budget (limited initial cost) can be identified by searching for the Pareto option with the lowest life cycle cost and an initial cost that is lower than or equal to the available budget.

7 Results

7.1 Economic assessment

The economic assessment (Fig. 4) revealed that the investment cost of the alternatives differs to a greater extent than their life cycle cost. The initial cost was identified as the most important contributor to the life cycle cost, followed by the cleaning cost (Fig. 5). For the reference floor, the investment represented 48 % of the life cycle cost, while cleaning represented 41 % and heating 7 %. In the initial stage, the labour cost is slightly more important than the material cost.

Out of all analysed floor coverings, carpet led to the lowest investment and life cycle cost (single Pareto optimum). Blue stone from Asia[2] (China, Vietnam) required a higher investment but led to the second best life cycle cost, followed by cork. Of course, the function of the room should be considered too in order to choose an appropriate floor covering (e.g. kitchen: grease and/or acid resistance). If it is assumed that the inhabitants clean the floor (and the costs for the cleaning products are neglected) and thus the cleaning cost equals zero, both the importance of the costs and the preference of the floor coverings changes (light grey boxes in Fig. 4). For the reference floor, the investment then represents 77 % of the life cycle cost, while heating represents 14 %. The Pareto front now consists of several floor coverings, starting from carpet (lowest investment cost) followed by laminate, linoleum and blue stone from Asia.

A different thickness was identified as absolute optimum for the different insulation materials considered (see Fig. 4). For PUR (10 cm) and EPS (12 cm) over the slab and EPS (12 cm) under the slab, the maximum available thickness on the current market was the absolute optimum. Greater thicknesses were composed of a double insulation layer and therefore resulted in an important extra investment cost (labour). Out of all analysed insulation materials, PUR foam led to the lowest initial and life cycle cost. Insulation under the floor bed requires a lower investment and life cycle cost than the insulation over the floor bed which can be explained by the required extra levelling course for the latter.

[2] Floor tiles of blue stone from Asia are very common in Belgium despite the availability of local blue stone. This is because the former are much cheaper.

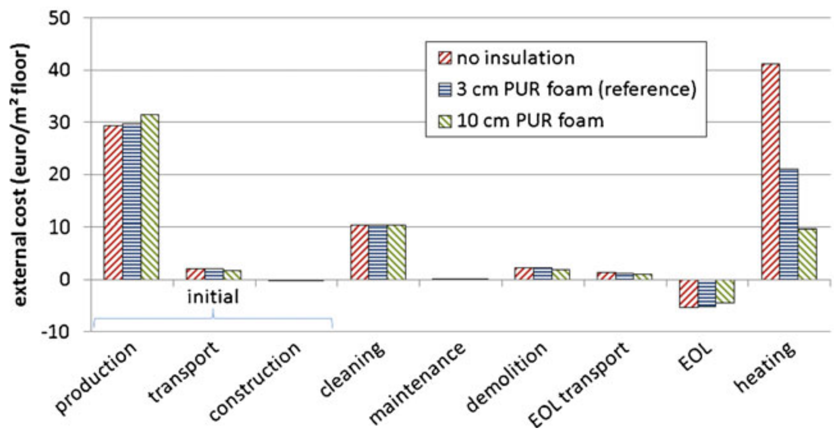


Fig. 7 Floor without insulation, 3 cm PUR foam (reference) and 10 cm PUR foam: distribution of the external cost over the life stages and processes

7.2 Environmental assessment

From an environmental point of view (Fig. 6), the life cycle cost was determined above all by the heating demand. A 27 % reduction of the life cycle external cost of the floor according to common practice to date was achieved by increasing the insulation level, and up to a 43 % reduction was achieved for existing non-insulated floors.

The difference between the insulation types (in life cycle environmental cost) was rather limited, indicating that the insulation level was more important than the type of insulation. One exception was the rock wool over the floor slab, which resulted in a higher initial and life cycle environmental cost than the other insulation materials. Resol board under the floor slab resulted in the lowest life cycle environmental cost. The absolute optimum for each of the insulation materials equalled the maximum foreseen insulation thickness, except for PUR foam (18 cm), PUR board under the floor slab (18 cm) and rock wool over the slab (12 cm).

The type of floor covering was important both in terms of initial and life cycle external cost. For the reference floor, both the initial and the heating costs contributed to an important extent to the life cycle cost (Fig. 7). For uninsulated floors, the heating cost was the determining factor, while for better-insulated floors (10 cm PUR), the initial cost contributed most to the life cycle external cost. A further investigation of the initial stage of the reference floor indicated that the ceramic tiles contributed most (56 %), followed by the concrete floor slab (31 %). The floor covering with the lowest external initial cost was linoleum. Laminate was identified as the sub-optimum and carpet as the absolute optimum.

Finally, the influence of the most important optimisation measures (insulation and floor covering) on the different impacts (expressed in euro/m^2 floor) was investigated (Fig. 8). For the comparison of the ceramic tiles and the laminate (left), the production, transport, construction, cleaning, maintenance, replacements, demolition, transport to EOL and EOL treatment of the tiles and laminate were considered. Choosing laminate instead of ceramic tiles mainly affected the emission of $PM_{2.5}$ (a reduction from 194 to 11 g, or thus of 95 %).

For the comparison of the floor with 3 and 10 cm PUR foam (right), the life cycle external cost of the complete floor was considered. An increase in insulation level mainly resulted in a reduction of the CO_2-equivalents (from 264 to 136 kg, or thus of 48 %) and of the depletion of fossil fuels (from 583 to 301 MJ surplus energy, or thus of 48 %).

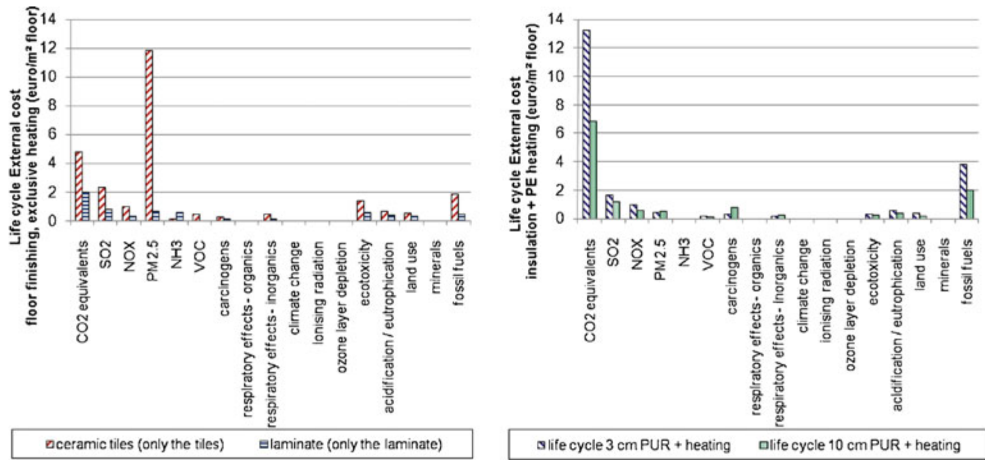
7.3 Internalisation of external cost

The life cycle environmental cost was small compared to the life cycle financial cost (9 % on average). If the financial cost of cleaning is not considered (assuming that the inhabitants clean the floor themselves), the importance of the life cycle environmental cost rises up to 15 % on average. A comparison of the environmental and financial cost during the different life cycle phases reveals the following numbers: 12 % for the initial phase, 43 % for heating, 2 % for cleaning, 2 % for maintenance and 2 % for replacements. If only the financial material cost is considered in the initial phase (not the labour cost), then the environmental cost equals 22 % of the financial cost. The relatively low importance on a life cycle base can thus be explained by the high labour/material cost ratio in construction.

Despite this rather small importance on a life cycle base, the analysis of the total cost revealed that several decisions did differ from the ones based on financial cost only. The most important were the following: The absolute optimal insulation level without budget restriction was increased (except for EPS and PUR board over the slab and PUR foam). The blue stone from Asia[3] led to a higher total initial cost than the ceramic tiles (reference) in contradiction to the financial cost. The screed based on anhydrite binder required a lower initial total

[3] For the modelling of the in- and outputs of the extraction process of Asian blue stone, the European electricity mix was changed for the Japanese mix (best available approximation). For the transport (distances, means) of the Asian blue stone to Belgium a detailed study was made by the BBRI.

Fig. 8 Influence of choice floor finishing and insulation level on the different environmental impacts considered (expressed in external costs/m^2 floor)



cost than the insulating screed with EPS aggregates of 10 cm thickness. Its financial initial cost, on the other hand, is higher than of the EPS screed alternatives.

7.4 Sensitivity analysis

Sensitivity analyses were made of the life span of the floor, the external cost of CO_2-equivalents, the number of eq. °days and the growth rate of energy prices. The *U* values of the floor on grade alternatives are summarised in Table 10 indicating the absolute optima based on financial cost for the different scenarios. The optima according to the basic scenario are indicated with a continuous circle. A dotted circle is used for an extended life span of 120 years and for a life span of 60 years but with a higher growth rate of energy prices (4 %). Both scenarios led to identical optimal thicknesses. A rectangle shows the absolute optima for an increased number (1,700) of degree days.

The absolute optimum thickness clearly depended on the insulation material. The prolongation of the life span, the increase of the growth rate of energy prices and the increase in eq. °days resulted in higher optimal thicknesses.

The absolute optima based on environmental cost equalled the maximum analysed insulation thickness for all materials (except for PUR board under the floor slab, PUR foam and rock wool board over the floor slab). An increase in the growth rate of energy prices did not influence these optimal thicknesses. An increase in life span, in eq. ° days and in the external cost of CO_2-equivalents resulted in the maximum considered thickness as absolute optimum.

8 Discussion and conclusions

It can be concluded that the heat resistance (insulation value) and the choice of floor covering mainly influence the life cycle environmental impact of the floor on grade, while the latter is most determining for the financial cost. The production process of the floor coverings mainly influences the environmental impact, while the financial cost is mainly determined by the investment and cleaning cost. Due to these differences, decisions based on financial and environmental cost do not always coincide. Internalising the environmental costs enables to make straightforward decisions in case of such contradictions. However, because of the minor importance of the life cycle environmental costs compared to the life cycle financial costs, the latter are most dominant and influence the decisions to the greatest extent. This was proven to be due to the high labour/material cost

Table 10 Summary of the *U* values (watts per square metre kelvin) of the floor on grade, indicating the financial cost optima for the different scenarios (Allacker 2010, p. 196)

	3 cm	4 cm	5 cm	6 cm	8 cm	10 cm	12 cm	15 cm	18 cm	20 cm	21 cm	24 cm
PUR over	0.37		0.28		0.20	0.17		0.13		0.10		
PUR under		0.33			0.21	0.18	0.15		0.10			0.08
PUR foam	0.38	0.33	0.29	0.26	0.21	0.18	0.15	0.13	0.11		0.10	
resol over		0.32			0.20	0.17	0.15	0.11				0.08
resol under		0.33			0.21	0.18	0.15		0.11			0.08
EPS over		0.39			0.27	0.23	0.21		0.15			0.12
EPS under		0.40			0.28	0.24	0.21		0.15			0.12
XPS over		0.39			0.27	0.23			0.15	0.14		
XPS under		0.40			0.28	0.24	0.21		0.15			0.12
rock wool over	0.46		0.37		0.29	0.25	0.23		0.17			0.13

Financial cost optima 120 years combined with growth rate energy prices 4 % => all largest foreseen thicknesses are most optimal. If no indication is made, this means the absolute optimal thickness for the specific scenario is equal to the previous scenario

financial cost optima 60 years, basic scenario; financial cost optima 120 years, basic scenario and 60 years, growth rate energy prices 4 %; financial cost optima 1,700 equivalent degree days

ratio. If the labour cost would reduce in future (or if cleaning would not be included, i.e. cleaning is done by the building owner 'at no cost'), the environmental cost would gain importance and would influence the decisions more. Despite the low importance on a life cycle base to date, some of the decisions based on the sum of the financial and external costs revealed to differ from the ones based on financial cost only. It seems, however, important to consider financial and external costs separately as both proved to lead to different decisions and thus contain important information for the decision maker. If in future the financial costs would change according to the above or if the willingness to pay to avoid environmental damage would increase, on the long run internalisation of the environmental costs seems a valid way to reach more sustainable building solutions.

9 Recommendations

Both from a life cycle financial and environmental point of view, the floor on grade in residential buildings in the Belgian context should be insulated better than current common practice. The insulation level should be higher from an environmental perspective compared to the preferred thickness from a financial point of view. Because it is difficult, if not impossible, to add insulation to the floor on grade during the life cycle of a building, it is recommended to foresee such a significant insulation level right from the start. The necessary investment for this extra insulation thickness (compared to common practice to date) proved to be limited (<10 %) considering the same insulation material. Opting for other insulation types—with a lower environmental impact—might lead to an extra required investment of up to 40 %. Because of the relatively minor importance of the environmental external costs, internalisation of these does not result in a big difference in choice of insulation material. However, decisions on the insulation level based on financial life cycle costs (60 years) instead of investment costs solely proved to be an important step in reducing the environmental life cycle impact of the floor on grade. The order of preference of the floor covering was clearly influenced by internalisation of the external environmental costs. Further refinement (increase) of the monetary values of certain environmental impacts, however, is recommended to increase the importance of the environmental costs in decision making and thus make internalisation a valid approach to change our behaviour more drastically.

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References

a.a. (2007) Belgisch Staatsblad 13.11.2007, bijlage—transmissie referentie document. Belgian Government, Brussels

ABEX (2009) www.abex.be. Accessed Jun 2009

Allacker K (2010) Sustainable building: the development of an evaluation method. Dissertation, Katholieke Universiteit Leuven. https://lirias.kuleuven.be/handle/123456789/267749. Accessed Jan 2012

Allacker K, De Nocker L (2012) An approach for calculating the environmental external costs of the Belgian building sector. J Ind Ecol. doi:10.1111/j.1530-9290.2011.00456.x

Ammar C, Longuet M (1980) Belgian requirements about buildings service life. Durability of building materials and components. American Society for Testing and Materials (ASTM), West Conshohocken, pp 77–90

ASPEN (2008a) ASPENINDEX—Nieuwbouw, editie 39. ASPEN, Antwerp

ASPEN (2008b) ASPENINDEX—Onderhoud, ombouw, editie 39. ASPEN, Antwerp

Bare J, Hofstetter P, Pennington D, Udo de Haes H (2000) Life cycle impact assessment workshop summary—midpoints versus endpoints: the sacrifices and benefits. Int J Life Cycle Assess 5 (6):319–326

BBRI (1994) Technische Voorlichting 193—Dekvloeren deel 2—uitvoering. Carlo De Pauw, Brussels

BCIS (2006) Life expectancy of building components—surveyors' experiences of buildings in use—a practical guide. Connelly-Manton, London

Belgian Federation of Timber import (Belgische Federatie van de Houtinvoerhandel) (2007) Wood market trends in Belgium 2006. Belgische Federatie van de Houtinvoerhandel vzw, Brussels

Castella PS, Blanc I, Ferrer MG, Ecabert B, Wakeman M, Manson J, Emery D, Han S, Hong J, Jolliet O (2009) Integrating life cycle costs and environmental impacts of composite rail car-bodies for a Korean train. Int J Life Cycle Assess 14:429–442

Davidson MD, Hof AF, Potjer B (2002) Update Schaduwprijzen. Financiële waardering van milieu-emissies op basis van Nederlandse overheidsdoelen (Update of Shadow prices. Monetary valuation of environmental emissions based on Dutch government targets). CE, Delft

De Nocker L, Bronders J, Liekens I, Patyn J, Smolders R, Engelen G (2007) Uit- en doorwerking van langetermijndoelstellingen in het milieu- en natuurbeleid, Finaal rapport Case Grondwater. VITO, Mol (not publically available)

De Troyer F (2007) Bouweconomie en Systeembouw. ACCO, Leuven

Dexia Bank (2007) De spaarrekening: interessant als belegging? Nieuwsbrief van Dexia Bank, January 2007: 1

MINEFI-DGTPE (2007) La filière bois au Gabon, Mission économique. www.legabon.org/articles_pdf/filiere_bois_minefi_mai_2007.pdf. Accessed May 2007

D'haeseleer W et al (2007) Belgium's energy challenges towards 2030. Commission Energy 2030, Brussels. www.ce2030.be. Accessed 19 Jun 2007

DPWB (1984) Ontwerp en thermische uitrusting van gebouwen, Deel 1 en 2. DPWB, Brussels

EC (2006) World energy technology outlook 2050 (WETO-H2). EC, Brussels

Ecoinvent (2009) www.ecoinvent.org. Accessed July 2009

European Commission (2008) ExternE. www.externe.info. Accessed Aug 2009

European Commission (2009) eurostat—your key to European statistics. http://nui.epp.eurostat.ec.europa.eu/nui/setupModifyTableLayout.do. Accessed Oct 2009

Federaal Planbureau (2007) Economische vooruitzichten 2007–2012. Federaal Planbureau, communiqué dd. 11 May 2007. www.plan.fgov.be. Accessed Jun 2007

FOD economie, K.M.O., Middenstand en Energie (2009) http://statbel.fgov.be/nl/statistieken/cijfers/economie/bouw_industrie/gebouwenpark/index.jsp. Accessed Dec 2009

Frère H (2008) Etat de la consommation du bois an Belgique. Rencontres filières bois, 17 March 2008

Holland M, Pye S, Watkiss P, Droste-Franke B, Bickel P (2005) Damages per tonne emission of PM2.5, NH3, SO2, NOx and VOCs from each EU25 Member State (excluding Cyprus) and surrounding seas. AEA Technology Environment, Didcon, Oxon

den Hollander ThGM, Kuhlmann WH, Steenhuis JD, Veldkamp IHJT (1993) Woningbouwkosten—Groot onderhoud en renovatie. Misset Bouw, Doetinchem

Inies (2009) www.inies.fr. Accessed Jul 2009

Institut forestier national (Ifn) (2008) La forêt en chiffres et en cartes. www.ifn.fr. Accessed 2008

ISO 14040 (2006) Environmental management—life cycle assessment—principles and framework. International Standards Organization, Geneva

ISO 14044 (2006) Environmental management—life cycle assessment—requirements and guidelines. International Standards Organization, Geneva

ISO 15392 (2008) Sustainability in building construction—general principles. International Standards Organization, Geneva

Marler RT, Arora JS (2004) Survey of multi-objective optimization methods for engineering. Struct Multidiscip O 26(6):369–395

Mizsey P, Delgado L, Benko T (2009) Comparison of environmental impact and external cost assessment methods. Int J Life Cycle Assess 14:665–675

Norris GA (2001) Integrating life cycle cost analysis and LCA. Int J Life Cycle Assess 6(2):118–120

Ott W, Baur M, Kaufmann Y, Frischknecht R, Steiner R (2006) NEEDS (New Energy Externalities Developments for Sustainability)—assessment of biodiversity losses. Ecoconcept AG, Zurich

Pasman WPM, van Groningen JA, Scholten C, Veldkamp IHJT (1993) Burgerwerk en kleine aannemingen—onderhoud en herstel. Misset Bouw, Doetinchem

Sáez CA, Requena JC (2007) Reconciling sustainability and discounting in cost–benefit analysis: a methodological proposal. Ecol Econ 60:712–725

Swarr TE (2006) Life cycle management and life cycle thinking: putting a price on sustainability. Int J Life Cycle Assess 11(4):217–218

Swedish Forest Industries Federation (2007) The Swedish Forest Industries, facts and figures 2007. www.forestindustries.se. Accessed May 2007

Torfs R, De Nocker L, Schrooten L, Aernouts K, Liekens I (2005) Internalisering van externe kosten voor de productie en de verdeling van elektriciteit in Vlaanderen. MIRA, Mechelen

UPA-BUA (2009) Borderel van eenheidsprijzen. Union Royale Professionelle des Architectes—Koninklijke Beroepsunie van de Architecten, Brussels